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GREENHOUSE AUTOMATION, ILLUMINATION AND EXPANSION STUDY FOR MARS DESERT RESEARCH STATION

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A partially or fully autonomous food production facility is one of the most important elements in any extraterrestrial settlement. The GreenHab, the greenhouse of the Mars Desert Research Station (MDRS), provides an excellent opportunity for an expansion study, considering it both as an experimental facility for crop growth but also as a food provider for the crew. The current GreenHab is a basic horizontal cylindrical structure divided into two parts. The larger part is used for vegetables growth over the season, which are harvested and consumed by the latest crews in rotation at the station. It also provides the opportunity to perform experiments within the greenhouse facility. The second part is dedicated to the crew well-being in form of a Zen garden with flowers.

The MDRS GreenHab is an independent module linked to the main habitat through a corridor. Full integration of the greenhouse module into the habitat would be preferable since on top of participating to food production it could directly support air revitalization and water recycling, which are life-critical processes related to all human operations in the base. The MDRS internal environment suffers from extremely low humidity (e.g., 18- 22 % during February) due to its location in the high desert of Utah and also due to its heat and ventilation air conditioning system design that is not integrated with the other base subsystems. An integrated greenhouse could improve the atmosphere quality and decrease crew health risks as well as increase their comfort and work efficiency. Greenhouse systems are not hazardous (in opposition to some power systems requiring specific distance from the base due to possible life endangering failures) and thus do not require protective zoning apart from the habitation unit, which makes their integration into the habitat a plausible scenario.

This paper presents number of approaches and options for the GreenHab automation, illumination and capacity expansion based on various research, production and base operations interests. Currently the GreenHab requires much crew time for maintenance and daily operations, which could be reduced by at least a third using automation techniques. The use of supplemental lighting would also greatly improve light conditions inside the GreenHab, therefore enhancing crop growth and yield of the greenhouse. There are numerous options for the GreenHab expansion such as: modular, dome radial, detached, attached from pre-fabricated components, self-deployable or built of in-situ resources depending on the level of habitat and greenhouse simulations and structures fidelity.

I. INTRODUCTION

Future settlements on Mars will need to include facilities for food production in order to sustain human crews living there. Indeed resupplying consumables would involve a very large number of launches associated with very high costs which would make the base on Mars unsustainable [1]. This can be achieved by using a combination of greenhouse modules and bio-regenerative life-support systems. In addition to providing food to the crew, higher plants also enable atmosphere regeneration by consuming CO2 of the crew and producing O2 [2].

Greenhouse modules and plant production in controlled environments have been tested for many decades. Experiments conducted in the Biomass Production Chamber (BPC) at the Kennedy Space Center (KSC), showed that very high yields can be achieved in controlled environments with optimizing environmental parameters [3]. The Higher Plant chamber of the MELiSSA (Micro-Ecological Life Support System Alternative) Pilot Plant is intended to be integrated in a fully closed loop of an artificial ecosystem [4]. The Arthur Clark Mars Greenhouse located on Devon Island and operated by the Canadian Space Agency (CSA), and the University of Guelph and the University of Florida, mainly focuses on greenhouse automation in extreme remote environment [5]. The Deutsches Zentrum für Luft und Raumfaht (DLR) / Evolution and Design of Environmentally-Closed Nutrition-Sources (EDEN) soon-to-be deployed greenhouse module at the Neumayer station in Antarctica will focus on technology development and operations testing in extreme environment [6].

The Closed Ecology Experiment Facility (CEEF) in Japan [7] and BIOS 3 in the former USSR [8] are among the few facilities which conducted (or still conduct) experiments on greenhouse modules along with human isolation studies.

The Mars Desert Research Station (MDRS) of the Mars Society in Utah provides scientists a unique environment to test technologies, operations, and science in a Mars-like environment. Since 2002, the MDRS is equipped with a greenhouse module (the GreenHab), which is accessible to the crew via a simulated pressurized corridor and hence without the need of Extra Vehicular Activities (EVAs).

Fig. 1: MDRS GreenHab and Habitat in Utah desert. View from the North.

The current GreenHab is a basic horizontal cylindrical structure (Fig. 1) divided into two parts: the larger part is used for vegetables growth over the season and to perform experiments within the greenhouse facility; the second part is a Zen garden with flowers for crew well-being Fig. 2. The structure of the GreenHab is very similar to a terrestrial greenhouse, made of polycarbonate translucent shell on metal and wooden framework. The sole source of light in the Greenhab is thus the sun, whose light is filtrated through this shell. The system is not airtight.

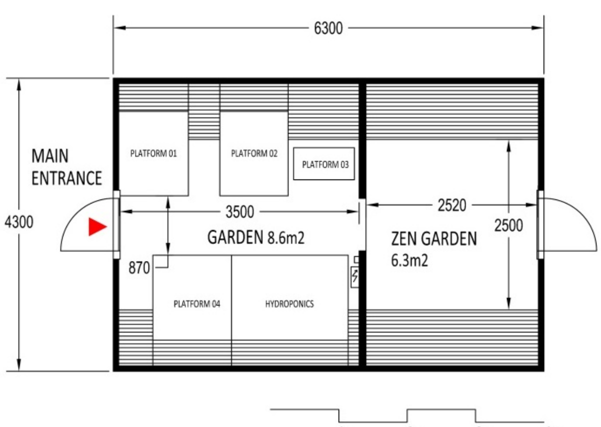

Fig. 2: GreenHab plan: the garden provides number of platforms for plants growth and experimentation. The zen Garden is dedicated to crew's relaxation.

In February 2014, Crew 135 successfully completed the Reliability and Redundancy (RAR) simulated Mars mission during which an optimization and expansion study of the GreenHab in terms of illumination and automation was performed. The overall goal of the RAR mission was to assess the reliability of the habitat's operational, mechanical, structural, and power systems as well as holistically assess its reliability and possible upgrades. To follow-up activities initiated in the frame of the DLR/EDEN group, this study looked also into current light systems inside the GreenHab as well as the addition of electrical light by measuring their light levels. An assessment of space use in the GreenHab was performed and recommendations for a more efficient use were given. Crew time was also measured to identify where this metric could be reduced in order to optimize astronauts' time within the facility.

II. ENVIRONMENTAL CONDITIONS IN THE GREENHAB

A remote thermometer/hygrometer display is placed in the habitat, enabling the crew to constantly monitor temperature and relative humidity in the GreenHab and take adequate measures when necessary (e.g. move young plants in the habitat for the night when temperatures are too low). When temperatures get too high, a fan automatically starts and blows hot air out, allowing colder air to enter.

Temperature in the GreenHab was measured every day at 9:00 (Fig. 3) and 17:00 (Fig. 4) using a Radioshack digital thermometer-hygrometer. These graphs give the variations in temperature over the entire mission.

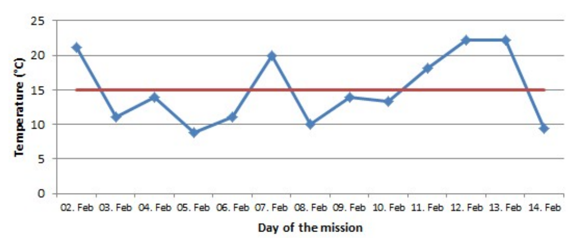

Fig. 3: Temperature variations in the GreenHab at 09:00 over the course of the mission.

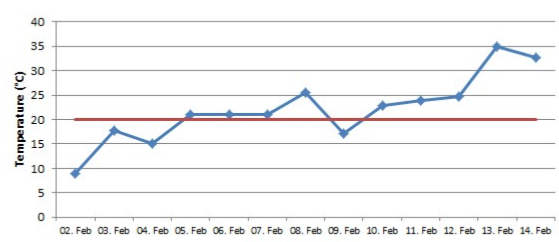

Fig. 4: Temperature variations in the GreenHab at 17:00 over the course of the mission.

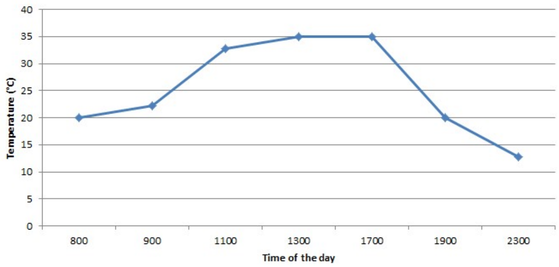

Fig. 5: Temperature variations in the GreenHab over the course of one day.

The average temperature at 9:00 was 15°c and 20°c at 17:00. However it is to be noted that temperature varied significantly from one day to the other.

Temperature variations over the course of one day are also reported (Fig. 5). This shows that there are great differences between day and night temperatures. The gradient on this particular day is 20°C.

Temperature measurements in the GreenHab were made on February 13, 2014 at different time of day and at various locations to estimate temperature gradients within the GreenHab itself using a portable thermometer Omega OS643 Omega Engineering, Inc., Stanford, CT, USA. There were eight measurement points as displayed on Fig. 6. The red dot indicates the position of the Radioshack digital thermometer-hygrometer.

The results of these temperature measurements are given in Table 1.. Th. = Thermometer located on the red dot; Med = Median; SD = Standard Deviation.

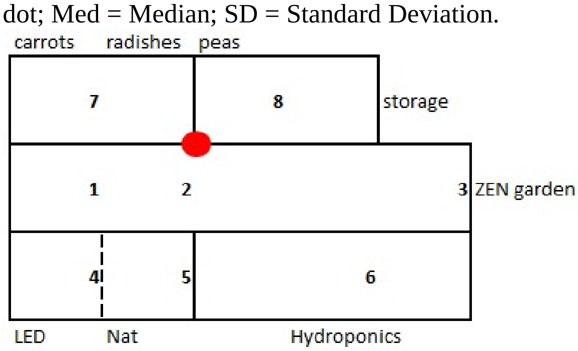

Fig. 6: Map of temperature measurement points within the GreenHab.

	9am	11am	1pm	4:30pm	7pm	11pm
Th.	22.22	32.78	35.00	35.00	20.00	12.78
1	23.00	33.00	40.00	33.00	16.00	10.00
2	22.00	32.00	38.00	33.00	15.00	10.00
3	23.00	30.00	42.00	34.00	15.00	10.00
4	20.00	32.00	30.00	27.00	14.00	10.00
5	22.00	29.00	32.00	27.00	14.00	9.00
6	23.00	34.00	35.00	33.00	16.00	11.00
7	27.00	31.00	31.00	28.00	16.00	9.00
8	26.00	32.00	31.00	27.00	14.00	9.00
Mean	23.25	31.63	34.88	30.25	15.00	9.75
Med	23.00	32.00	33.50	30.50	15.00	10.00
SD	2.25	1.60	4.61	3.24	0.93	0.71

Table 1: Temperature variations within the GreenHab at given times of the day.

The median and mean values are close to each other at any time of the day except at 1pm. This shows that the distribution of temperature is quite homogeneous within the GreenHab except at that time of the day. Indeed the standard deviation value at 1pm is 4.6°C. The least variations are observed from 7pm, when the sun is set. In the morning, the East side of the GreenHab is illuminated, which corresponds to points 7 and 8. This is shown in the temperature values, since they are in average 4 to 5°C higher than the rest of the GreenHab. In the afternoon and evening the sun illuminates the Zen garden and this can also be seen in the reported temperature values. This shows that a significant temperature gradient exists in the GreenHab, where temperature is thus not homogeneous.

Table 2 summarizes the relative humidity (RH) conditions in the GreenHab over the mission. Relative humidity varied from 11 to 23% with an average value of 17.4%. Since the first quartile is at 17% and the third quartile at 18% it means that 50% of the values were between 17 and 18%.

	RH in %
Mean	17.38
Median	17
Minimum	11
Maximum	23
3rd quartile	18
1st quartile	17
Standard Deviation	2.170

Table 2: Relative humidity mean, median, minimum, maximum, quartiles, and standard deviation values over the mission.

III. ILLUMINATION STUDY

III.I. Materials and methods

MDRS Crew 135 installed a red and blue LED flat circular lamp ("UFO") in the GreenHab which was donated to MDRS and left in the GreenHab after completion of Crew 135 mission, providing supplemental lighting. The spectroradiometer graph of this lamp is shown on Fig. 7. It was taken by a StellarNet Black Comet spectroradiometer (StellarNet, Inc., Tampa, FL). Light intensity assessment in the GreenHab was done by measuring light levels and light quality, and by performing an experiment comparing full natural light lettuce growth and natural with supplemental electrical light lettuce growth.

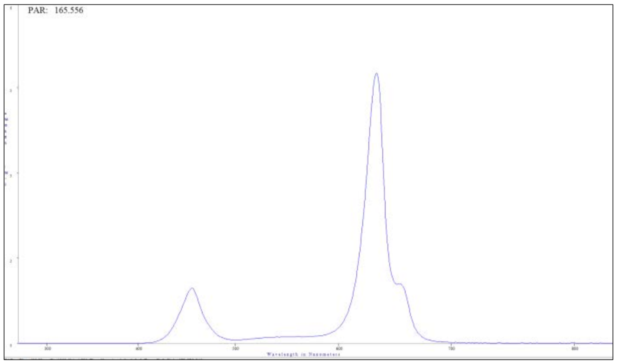

Fig. 7: Spectroradiometer graph of the red and blue UFO lamp.

An Apogee MQ 200 quantum sensor (Apogee Instruments, Logan, UT) was used in an automatic mode, taking a measurement every 30 seconds and then averaging over 30 min. This enabled to assess natural light quantity in the GreenHab. The spectroradiometer measurements were done at different time of the day and enabled to assess light quality in the GreenHab.

An experiment with young lettuce sprouts and three-week old lettuce plants was conducted: one treatment was placed under natural light and one treatment under natural and supplemental red and blue LED light (Fig. 8 and Fig. 9). The sunrise was around 7:00 and the sunset around 17:30. The LED lamp ran from 8:00 till 19:00, thus providing an hour and a half of extra light per day. The total photoperiod of these plants was 12 hours. A separation wall made of Panda plastic film was set between the two treatments to avoid light contamination but it did not run all the way up to avoid blocking sunlight in both treatments. The LED lamp was placed 64 cm from the shelf. A RYOBI Power Usage meter (E49CM01 120 VAC 50-60 Hz 15A Max) measured the electricity consumption of the lamp.

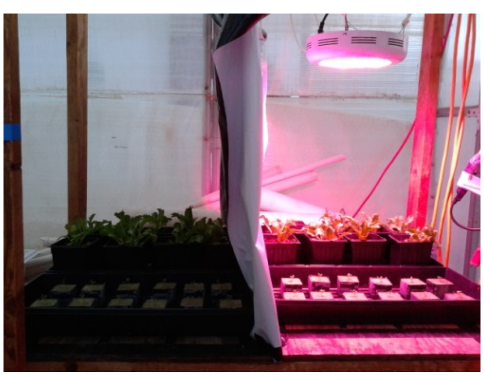

Fig. 8: Photo of the experimental set up in the GreenHab. Left: treatment with natural light only. Right: treatment with natural and supplemental LED light.

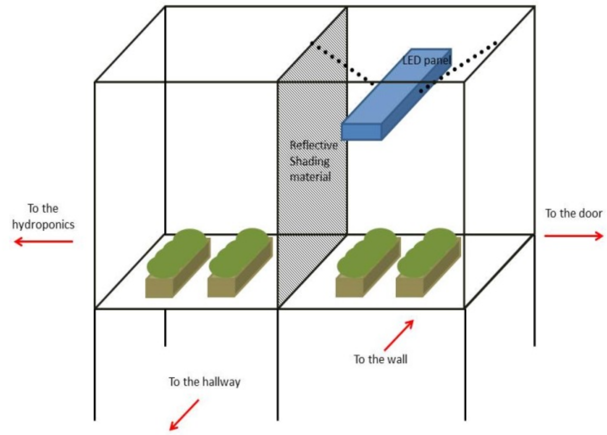

Fig. 9: Schematic of the experimental set-up in the GreenHab.

Two cultivars of lettuces (*Lactuca Sativa*) were grown: Ithaca and Mint Crisp from rareseeds.com, Baker Creek Heirloom Seed Co. (2278 Baker Creek Road, Mansfield, MO 65704). Half of the lettuces were planted in soil by Crew 133, three weeks before the start of Crew 135's mission.

The other half was planted on 02/02/2014 in rockwool mineral fibers Mini Blocks from Grodan, Rockwool B. V. (Industrieweg 15, 6045JG Roermond, The Netherlands). Since water at MDRS is very limited, the solution used to water all plants in the GreenHab came from the hydroponic tank (mix of water and nutrients), used for another growth experiment. This solution was mixed with a fertilizer FOXFARM Soil & Fertilizer Company, Instant Concentrate Grow Big Liquid Plant Food for Lush Vegetative Growth (NPK 6 – 4 – 4) and used to water the lettuces described above. On top of bringing critical nutrients to the plants, it also enabled to bring the pH of the solution down from 7 to 5.5.

For germination, the rockwool plant starters were set in the solution (pH 5.5) for ten seconds. Then two lettuce seeds per hole were set and the whole was covered and lid taped to keep humidity around 100%. This small germination device stayed in the GreenHab during the day but was brought inside the habitat at night in order to limit temperature differences on the young seedlings.

At the end of the experiment the following data were collected (Fig. 10): hypocotyl and leaves length, plant width, number of leaves, and leaves fresh mass using a scale from Denver Instrument Company XL-500/ZU.

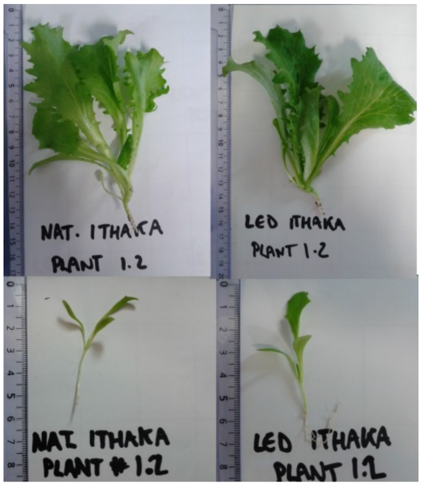

Fig. 10: Lettuces cultivar Ithaka on harvest date

III.II. Results and discussion

Light measurements in the GreenHab

Fig. 11 gives the average Photosynthetic Photon Flux (PPF) variation over one day within the GreenHab on the experiment shelf. The values given are averaged from measurements taken from 02/06 to 02/14.

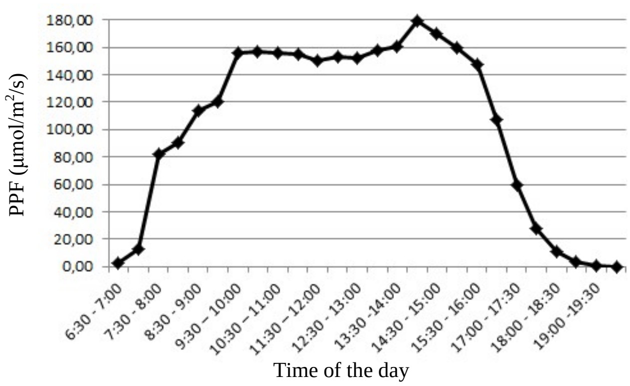

Fig. 11: PPF variations over one day on the experiment shelf in the GreenHab, averaged over eight days.

This shows that during seven hours of the day the PPF is about 160 µmol/m^2/s, with the maximum value reached being 180 µmol/m^2/s. This does not provide enough light to lettuces which need about 200-300 µmol/m^2/s during 16 hours for optimal growth [9].

Fig. 12 gives three spectroradiometer scans taken in the GreenHab at three different time of the day: at 8:00 on 02/04, at 12:30 on 02/11, and at 16:00 on 02/03. As expected, the biggest difference observed between the scans occurs in the visible range (400-700 nm), when the sun intensity varies.

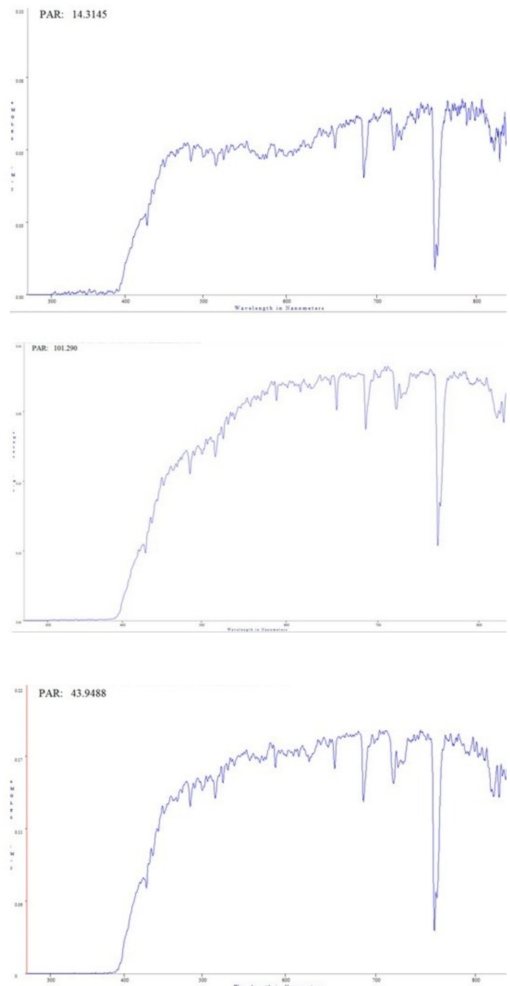

Fig. 12: Spectroradiometer scan taken at 08:00 (top), 12:30 (middle) and 16:00 (bottom).

Lettuce Growth experiment

Results for the lettuce growth experiment are summarized in Table 3, Table 4, and Table 5.

		Hyp length (cm)	Difference
Old lettuces			
Natural	Ithaca	1.068	0%
	Mint Crisp	0.578	0%
LED	Ithaca	0.913	- 14.6 %
	Mint Crisp	0.600	+ 3.8 %
Young lettuces			
Natural	Ithaca	1.877	0%
	Mint Crisp	1.625	0%
LED	Ithaca	1.508	- 19.6 %
	Mint Crisp	1.170	- 28 %

Table 3: Hypocotyl length in both treatments for old and young lettuces. Included the difference in % of length between all natural and natural with supplemented LED.

		Fresh mass (g)	Difference
Old lettuces			
Natural	Ithaca	2.520	0%
	Mint Crisp	3.165	0%
LED	Ithaca	3.051	+ 21. 1%
	Mint Crisp	3.506	+ 10.8 %
Young lettuces			
Natural	Ithaca	0.052	0%
	Mint Crisp	0.068	0%
LED	Ithaca	0.070	+ 33.8%
	Mint Crisp	0.077	+ 12.7%

Table 4: Fresh mass in both treatments for old and young lettuces. Included the difference in % of mass between all natural and natural with supplemented LED.

		Number of leaves	Difference
Old lettuces			
Natural	Ithaca	7.000	0%
	Mint Crisp	8.667	0%
LED	Ithaca	7.750	+ 10.7%
	Mint Crisp	9.125	+ 5.3%
Young lettuces			
Natural	Ithaca	1.000	0%
	Mint Crisp	1.833	0%
LED	Ithaca	1.000	0%
	Mint Crisp	1.900	+ 3.6%

Table 5: Number of leaves in both treatments for old and young lettuces. Included the difference in % of number of leaves between all natural and natural with supplemented LED.

For old and young lettuces and both cultivars, the hypocotyl of lettuces grown under LED lights was shorter (except for the old Mint Crisp), up to 28% shorter in the case of the young Mint Crisp. This is a clear indicator that the lettuces under supplemental LED light received more light and were healthier. Indeed an elongated seedling hypocotyl can disturb plant growth and development since it can bend and break. The fresh mass was larger for lettuces grown under supplemental LED lights, up to almost 34% more in the case of the young Mint Crisp. This shows that lettuces benefitted from supplemental LED light, even the older ones which had already spent 3 weeks under natural light only. Finally lettuces grown under supplemental LED light developed more leaves than the one grown under natural light only.

This experiment suggested that the addition of supplement electrical lighting in the GreenHab could greatly improve vegetable mass produced by almost 25% over the season and this recommendation was given to the MDRS management as a way to make the GreenHab more efficient and profitable for crews coming early in the season.

IV. GREENHAB OPTIMIZATION

IV.I Temperature – Humidity recording automation

Temperature and humidity readings are to be taken every day twice a day. This also is constraining for the greenhouse officer and an automatic system would make their task easier.

In addition, this system would detect critical temperatures and relative humidity levels in a shorter time than the greenhouse officer. Indeed big temperature variations and extreme temperatures can be very detrimental for plant growth. In February 2014 temperature variations were great (from 0°C in the early morning to over 35°C on sunny days), despite a running heater and fans to adjust it. Currently relative humidity levels are very low (17-18%), which is detrimental for optimum plant growth and development. Indeed low relative humidity increases transpiration rates, which can have a negative impact on crop yield [10].

A control loop which would regulate the temperature inside the GreenHab would have a double advantage by making the greenhouse officer task less constraining and by reducing the risk of plant loss and bad yield by making temperature variations smaller. A fan already runs when temperatures exceed a certain threshold, so this could be done with a heater when temperatures fall below a certain threshold. Nighttime and daytime temperatures could be set and variations could be allowed within 1°C.

But such a control loop would not be efficient without reducing the heat losses in the GreenHab. Currently there is no thermal insulation, the outer shell is only made of a double hard plastic walls and ceiling. An actual insulation layer to the structure might interfere with incoming light but would greatly improve temperature conditions in the Greenhab. It would also reduce the energy burden of having a heater run the whole night to countermeasure heat losses. A better insulation of the GreenHab would also mean a better control of the relative humidity levels.

IV.II Crew Time analysis

Crew time was recorded in the GreenHab for crew 135 (from 02/03 till 02/14) but also for two other crews following, 139 and 140 (from 03/29 till 04/27). The person working in the greenhouse was asked to fill in a short table each time they worked in the GreenHab, mentioning the date and time of the day, the activities performed as well as the duration of the task. Results are summarized in Table 6.

	Crew time per day (min)
Average	44.7
Median	35
Max	245
Min	10

Table 6: Crew Time average, median, maximum and minimum spent in the GreenHab over three missions, during crew 135, 139, and 140 rotations.

The average time per day spent in the GreenHab to take care of plants is about 45 min and the median time is 35 min. This is to take care of about 5 m^2 of plants and ranges from watering and taking readings to harvesting and transplanting plants. The daily tasks are watering, covering/uncovering plants, taking temperature readings, and checking plants health. The tasks which are more exceptional are transplanting and planting as well as harvesting. Finally there are also maintenance tasks such as renewing the hydroponic tank or setting up insect traps.

Based on crew 135 measurements, a time division per task was done, as displayed in Table 7.

	Average time (min) per day
Daily operation	
Watering	10
Covering	5
Taking measurements	5
Plant health status checks	5
Exceptional operations	
Transplanting/Planting	90
Harvesting	120
Maintenance	
Renewing hydroponic tank	45
Setting up insect traps	30

Table 7: Crew Time division per task over the course of crew 135 rortation.

As of February 2014 no task in the GreenHab is automated and the greenhouse officer is responsible for doing all of them. Although 45 min per day is not a time-consuming task, it should be underlined that this is to be done on top of other science experiments and only accounts for 5 m^2 of plants. When the GreenHab is used to sustain crew's diet and thus more plants are grown (about 500 m^2 to fully sustain a 4-person crew), this value will increase and one or two crew members will have to be strictly dedicated to plant cultivation. Therefore it is advised to transition to a fully automated hydroponics system in the GreenHab. A space greenhouse module probably would have an automatic seeding and harvesting system as well as an automated watering system.

A first step in this transition could consist in having an automatic dripping system on a timer, watering each pot, like the one often used in amateur gardening. This would eliminate the watering constraint from the greenhouse officer duties.

With an automatic watering system and an automatic temperature and humidity recording system, 15 minutes per day could be spared to the greenhouse officer, which accounts for a third of the daily time spent in the GreenHab.

IV.III Better use of available space

Space to actually grow vegetables in the GreenHab is very limited compared to the total available space because necessary equipment and material for plant growth such as bag of soils, nutrients, and pots are stored inside the GreenHab (status of February 2014). As shown on Fig. 13, this is using precious growth space and could easily be fixed by having a storage room outside of the GreenHab itself. A suggestion would be to have it at the end of the corridor leading form the habitat to the GreenHab.

Then to fully utilize all growing space available in the GreenHab, multiple-level shelves are advised. Given the height of the GreenHab, these shelves could have three levels, without creating another hazard for humans by forcing them to use a high ladder. Three-level shelves could increase the plant production by three compared to the quantity currently grown in the GreenHab. Implementing such a solution would mean that electrical lighting would be necessary to provide lighting to plants located on lower shelves.

Fig. 13: The GreenHab shelves and current storage area seen from the entrance.

Crew 135 also recommended changing wooden shelves to plastic or non-rusting metallic shelves inside the GreenHab. Indeed, because of the harsh environmental conditions, wooden shelves are starting to wear out, which makes working in the GreenHab a hazardous activity due to the many splinters sticking out of the wooden shelves. The existing shelves could be varnished if changing the shelves themselves would be too much of a change at once.

V. EXPANSION STUDY

V.I Topographic/Habitat/GreenHab measurements

Extra Vehicular Activities (EVAs) were performed during the mission in order to determine the topographic environment surrounding the habitat. This enabled the crew to assess distances between outside structures, but also to get accurate measurements of the habitat and of the GreenHab (Fig. 16). It also enabled to find areas which would be available for an expansion.

A crew of two equipped with a digital laser rangefinder and distance measure Leica Disto D5, a light tripod and a notepad performed number of EVAs to acquire the approximate geometry of the surrounding environment. The surveying process was accompanied by difficulties mostly due to limitations given by the analog spacesuit helmets (view range, visibility). The data recorded through numerous sketches were later converted in CAD drawings inside the habitat.

The habitat is surrounded by steep-slope hills of geologically and statically unstable soil from the South and West. Flat terrain platforms are located between the South hills and to the North-East and East Cardinal. Since the South platform is used for manipulation with vehicles, for the deployment of EVA crews from the main airlock, and for access to power systems further behind the Southern hills, the Eastern and possibly North-eastern sides were selected for greenhouse expansion studies (see Fig. 14).

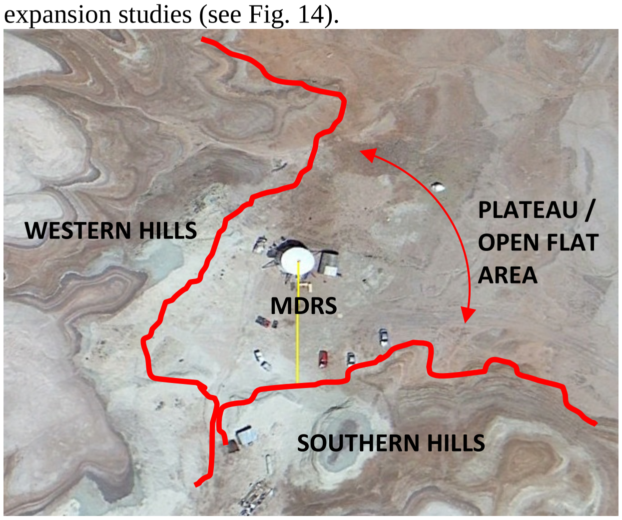

Fig. 14: Satellite image of the MDRS site. Arrows indicate area available for expansion - Source: Google Earth.

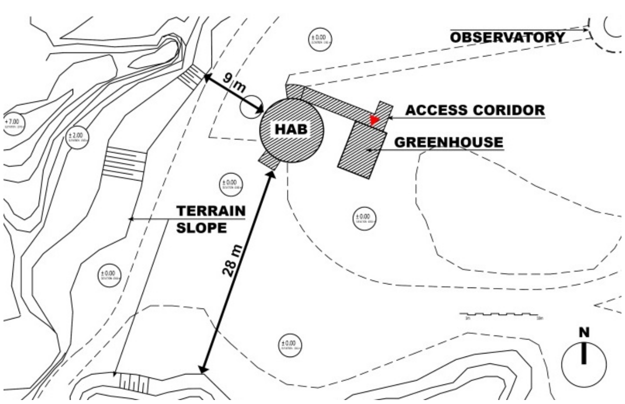

Fig. 15: MDRS systems scheme in relation to the surrounding terrain.

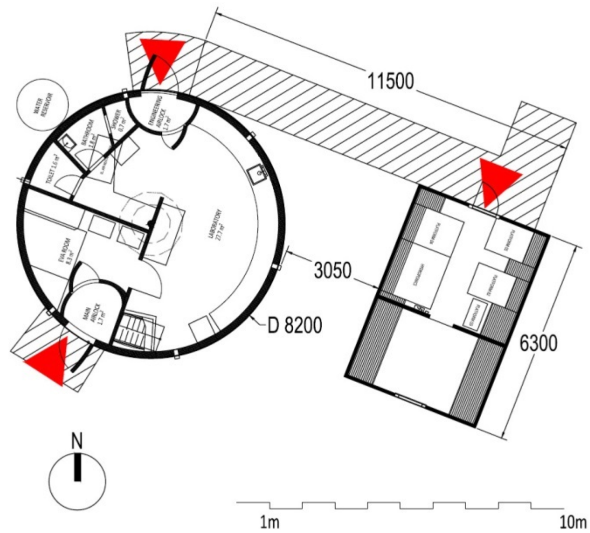

Fig. 16: Current configuration. MDRS habitat (left - with two airlocks one on the North and one on the South) and GreenHab orientation and mutual disposition. The GreenHab is accessible from the North using simulated pressurized corridor. GreenHab is equipped with service access from the South. Dimensions are in millimeters

The current greenhouse is located East of the habitat with access from the North 1361 m above the sea level. The polycarbonate structure of the GreenHab is placed three meters from the habitat (Fig. 16, Fig. 17).

Fig. 17: View on GreenHab and habitat from East.

V.II Greenhouse expansion options

There are number of options for the greenhouse expansion some of which are presented in this chapter. The main design and expansion drivers are:

- Modularity for ease of fabrication and multiplication
- Integration with habitat for simplification of Environmental Control and Life Support System (ECLSS) and automation systems
- Attachment and integration with habitat for maximum efficiency of interconnection of air and water systems.

Modular multiplication of the current small horizontal cylinder is thus one possible option. Although it may be perceived as the simplest one regarding fabrication, deployment or construction (since the cylindrical volume fits well the launcher's payload shroud), the modular system does not provide larger unified volume, for integrated ECLSS and possible robotic systems for automation (Fig. 18). Modular cylinders would be always prefabricated for automated or semi-automated deployment.

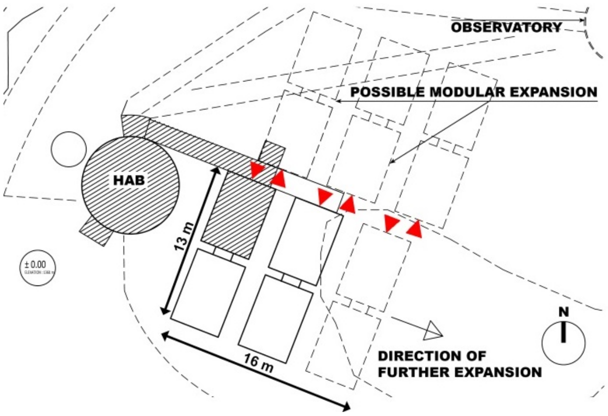

Fig. 18: Modular option based on rigid or inflatable horizontal cylinders.

Another option is a detached dome while keeping the existing GreenHab and corridors. The detached dome would be deployed as an independent structure without disturbance of the current systems. The benefits are in complete independence of geometrical and dimensional parameters as the connection to the main habitat would be through an extended existing corridor. Further automation and ECLSS operations inside the radial structure would be more convenient than in multiple small modules. The detached dome would have to be connected with powered fans with the habitat for air revitalization and exchange (Fig. 19). This geometry would combine rigid and deployable structural elements with inflatable internal bladder for pressurization and hermeticity.

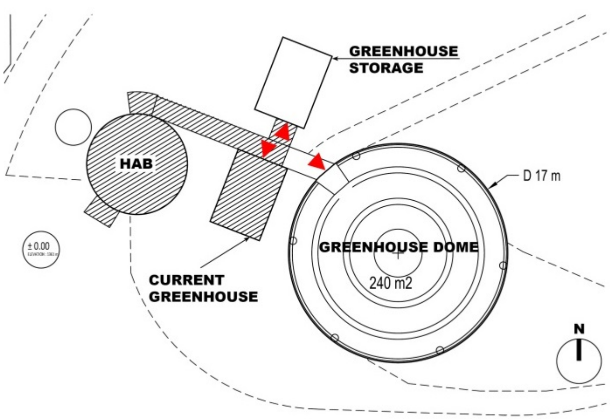

Fig. 19: Detached dome option while preserving current GreenHab.

Another option addressing direct attachment to the habitat and large volume is a half-dome geometry (Fig 20). The symmetrical composition allows for petal-like rigid and deployable components, similar to dome solution, equipped with an inflatable internal bladder that would be deployed at the end.

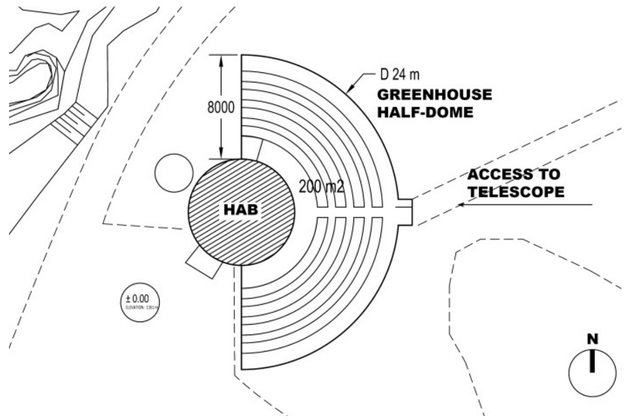

Fig 20: Attached half-dome concept.

Both concepts of dome and half-dome can be composed of pre-fabricated components transported from Earth but also from in-situ materials e.g., for the load-bearing structures of the dome ribs and walls. The half-dome geometry is not as suitable for pressurization as the dome geometry though.

A compromise between the detached large dome structure and half-dome could be the final concept of attached moon-shape dome. This solution has all benefits of half-dome, detached dome and can be fabricated and constructed by similar ways as well (including full prefabrication).

The moon-shape dome (Fig. 21) benefits of radial configuration for automation purposes, large volume for ease of air revitalization, direct attachment to the habitat for ease of air exchange, water and waste exchange, and having a dome pitch allows for placement of a water tank and water distribution and collection system providing benefits of water gradient and shielding from the top (Fig. 22).

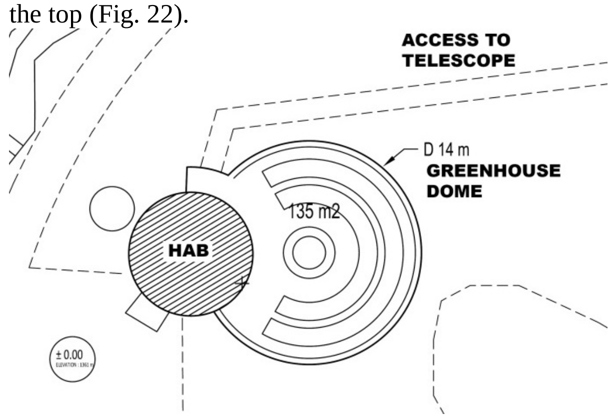

Fig. 21: Moon-shape greenhouse concept.

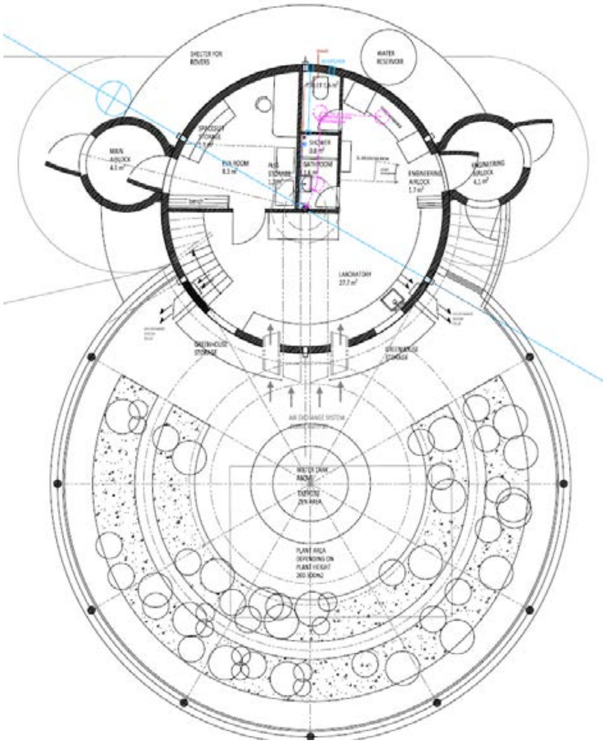

Fig. 22: Moon-shape greenhouse concept in higher level of detail showing plant beds, air exchange systems and connection to the habitat.

VI. CONCLUSIONS

Lighting conditions in the GreenHab are not optimum for plant growth in February lighting conditions. The light intensity reaching the plants is too low and the photoperiod too short. But this can easily be fixed by adding supplemental LED lighting in the GreenHab, which could improve vegetable production by 25% over a season.

Temperature and humidity are not optimum either. Temperature variations are too large, mostly due to the poor insulation of the GreenHab, and humidity levels are too low. This could be fixed with a better insulation system as well as an automatic temperature and humidity regulation system. It would improve crop yield as well as save time to the crew.

Better use of space in the GreenHab and use of multiple-level shelves would be a mean of increasing crop production as well.

Finally it is highly recommended to expand the GreenHab systems and integrate them into the habitat making it more realistic and safer for future space mission simulations. A fully independent crew supported by a greenhouse shall provide also higher level of life-critical systems redundancy and psychological support to the crew.

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